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A simple recipe to detect possible C-Odd effects in high energy $\bar{p}p$ and pp .

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Summary. We provide a theorem to suggest that $t = 0$ data may already be sufficient to detect possible asymptotic C-odd (*Odderon*) contributions. This can be done by comparing $\bar{p}p$ and pp $t = 0$ observables such as total cross sections, forward angular distributions and ratios of real to imaginary forward amplitudes for which well defined model independent correlations *must* exist which could already show up at RHIC energy but definitely at LHC energies.

A long debated and still unresolved puzzle of high energy physics concerns the possible existence of asymptotically important contributions to elastic reactions coming from the C-odd Regge trajectory known as the *Odderon* [1]. After the recent findings of the UA4/2 Collaboration [2] which finds $\bar{\rho} \equiv \frac{Re\,F_{\bar{p}p}(s,t=0)}{Im\,F_{\bar{p}p}(s,t=0)} = 0.135 \pm 0.015$ at $\sqrt{s} = 550\,GeV$, many authors [3, 4, 5] prefer to discuss the pp and $\bar{p}p$ data taking into account the *Pomeron* contribution only (and secondary Reggeon contributions, of course). The problem of the C-odd amplitude, however, remains entirely open both from the theoretical as well as from the experimental point of view. Indeed, if the Pomeron is interpreted as the trajectory interpolating C-even glueballs, unavoidably we are led to conjecture that a trajectory interpolating C-odd glueballs should similarly exist; next, pQCD calculations in the semihard region $m^2 \ll -t \ll s$ suggest an Odderon intercept larger than unity as for the Pomeron [6]. In addition, it turns out that an Odderon contribution is empirically absolutely necessary in order to obtain a high quality fit to all existing high energy elastic pp and $\bar{p}p$ data [7]. Its contribution, essentially hidden by the dominating Pomeron in the small $|t|$ region, becomes important at large $|t|$ in $\frac{d\sigma}{dt}$.

The question which we would like to answer in the positive is whether qualitative differences are to be expected at $t = 0$ if the Odderon exists. In the following, we *assume* that a C-odd contribution is asymptotically present; in this case, we will derive a number of correlations between the various observables at $t = 0$. It is our contention that these correlations should already be able to provide an indication of the Odderon provided we go to sufficiently high energies. We believe that LHC energies will definitely show such correlations and that even at RHIC energies we may already have an indication of them. This makes a qualitative difference with respect to previous considerations aiming at detecting the Odderon.

For simplicity, we begin with an explicit Ansatz and we later generalize our considerations so as to make our conclusions model independent.

1.- Let us assume the following *specific* asymptotic behaviors for the *Symmetric* (S) and *Antisymmetric* (A) amplitudes in which the pp and $\bar{p}p$ amplitudes can be decomposed

$$F_S \equiv \frac{1}{2}(F_{\bar{p}p} + F_{pp}) = is\left[A\,(ln\tilde{s})\,ln\left(\frac{B\,\tilde{s}^{\Delta}}{ln\tilde{s}}\right) - \frac{D_f}{\sqrt{\tilde{s}}}\right], \tag{1}$$

$$F_A \equiv \frac{1}{2}(F_{\bar{p}p} - F_{pp}) = -s\left[\epsilon\,ln^a\tilde{s} - \frac{D_\omega}{\sqrt{\tilde{s}}}\right], \tag{2}$$

where $F \equiv F(s, t = 0)$, $\tilde{s} = s\exp(-i\pi/2)$ and A (≥ 0), B (≥ 0), Δ (≥ 0), D's, a and ϵ are some real coefficients ($0 < a \leq 1$ is within the Regge-eikonal model the maximal behavior of F_A compatible with s-channel unitarity [8]) and the subscripts f and ω denote the subasymptotic C-even and C-odd Reggeons. A dimensional scale factor s_0 has been set =1 in all previous (and following) equations. Then we have, for large s

$$\frac{1}{8\pi}\left[\sigma_{tot}^{\bar{p}p}(s) - \sigma_{tot}^{pp}(s)\right] \equiv \frac{\bar{\sigma} - \sigma}{8\pi} = \frac{ImF_A}{s} \approx \epsilon\,a\,\frac{\pi}{2}\,(ln\,s)^{a-1} + \frac{D_\omega}{\sqrt{2s}}, \tag{3}$$

$$\frac{ReF_A}{s} \approx -\epsilon\,ln^a s + \frac{D_\omega}{\sqrt{2s}}. \tag{4}$$

If Δ is small (say $\Delta \approx 0.1$ [9]), the Froissart-Martin behavior [10, 11] for the total cross sections σ and $\bar{\sigma}$ will set in only at extremely high energies and will be $\propto A\Delta ln^2 s$. Given that the parameter ϵ (which according to our Ansatz *cannot be identically zero*) must anyhow be very small to comply with the data (say $\epsilon \sim 10^{-2} - 10^{-3}$), up to energies of the order of the TeV we will see the decrease of $(\bar{\sigma} - \sigma)$ due to the slow turning off of the secondary Reggeons coupling. Only at $\sqrt{s} \geq 1\,TeV$ can we expect it to begin approaching the term $\propto \epsilon\,(ln\,s)^{(a-1)}$ predicted

by (3). On the other hand, it is the term $\propto \epsilon\, ln^a s$ in (4) which is needed [7, 1b, 1c] to account for the behavior of $\frac{d\sigma}{dt}$ near the dip region and at large $|t|$ values in order to have a qualitatively good fit to the data. From our Ansatz (1, 2) we find $\bar{\rho} \sim \frac{A\,\Delta\,\pi\, ln\, s - \epsilon\, ln^a s + \frac{D_\omega + D_f}{\sqrt{2s}}}{A\,\Delta\, ln^2 s}$, and $\rho \sim \frac{A\,\Delta\,\pi\, ln\, s + \epsilon\, ln^a s + \frac{D_f - D_\omega}{\sqrt{2s}}}{A\,\Delta\, ln^2 s}$ (where $\bar{\rho}$ and ρ are the ratios of the real to the imaginary forward amplitudes for $\bar{p}p$ and pp respectively). Hence, at sufficiently high energies one predicts $\bar{\rho} < \rho$.

Most unfortunately, our knowledge of the pp elastic data is presently limited to the ISR energies $\sqrt{s} \approx 62\, GeV$ which is much much smaller than the scale $\approx 1\, TeV$ where we expect these effects to start showing up. At the ISR energies the values of ρ and $\bar{\rho}$ are practically the same (if anything, $\bar{\rho} \geq \rho$). It is, however, most interesting that the high quality fit of Ref.[7] empirically predicts $\bar{\rho} < \rho$ already at $\sqrt{s} \geq 100\, GeV$ which is a very good omen that at RHIC energies ($\sqrt{s} \approx 500\, GeV$) we should already see evidence of the asymptotic inequality $\bar{\rho} < \rho$.

2.- Let us now move to a more general case.

The full discussion of C-odd effects has been explicitly taken up in a simple Regge-eikonal model with $\mathbb{P}$ - O weak degeneracy [1] [8, 12, 13], $\alpha_{\mathbb{P}}(t) = \alpha_O(t) = 1 + \Delta + \alpha' t$ with unequal residues $\beta_{\mathbb{P},O}(t) = \lambda_\pm exp(\gamma_\pm t)$. This model reproduces (at least at a qualitative level) all the prominent features of $F_{\bar{p}p}$ and F_{pp} over the entire Regge domain ($s \gg 1 GeV^2$ and $0 \leq -t \leq const$) and gives a prediction of new phenomena [13] which coincides with the predictions coming from the extrapolations of the best χ^2 fit to all high energy pp and $\bar{p}p$ data [7]. In particular, at $t = 0$, this model gives a concrete realization of the amplitudes (1) and (2) with $a = 1$. In effect, the following exact expressions for F_S and F_A are obtained in the limit

[1] $\mathbb{P}$ for Pomeron and O for Odderon.

$s \to \infty, \gamma_+ = \gamma_- \equiv \gamma$ (secondary Reggeon contributions omitted) [13]

$$F_S = is \left[2(\gamma + \alpha' \, ln\tilde{s}) ln \left(\frac{e^C \sqrt{\lambda_+^2 + \lambda_-^2} \, \tilde{s}^{\Delta}}{2(\gamma + \alpha' \, ln\tilde{s})} \right) \right], \tag{5}$$

$$F_A = -s \left[2 \left(arctg \frac{\lambda_-}{\lambda_+} \right) (\gamma + \alpha' \, ln\tilde{s}) \right] \tag{6}$$

where $C \approx 0.577$ is the Euler constant. Thus, if the Pomeron and Odderon intercepts are equal to $\Delta \approx 0.08$, and the ratio of the Odderon/Pomeron couplings has the right order of magnitude ($\approx 10^{-2} - 10^{-3}$), this Regge-eikonal model gives a simple and selfconsistent way to take into account the C-odd effects in pp and $\bar{p}p$ elastic collisions. As already mentioned,in a Regge-eikonal model, the behavior $F_A \propto -sln\tilde{s}$ is the maximal one compatible with s-channel unitarity [8]. Let us also note that for $s \gg 1$ the following correlation holds $(\bar{\sigma} - \sigma)(\bar{\rho} - \rho) < 0$ which appears to be quite general and model independent[2].

3.- The general case.

From analyticity (forward dispersion relations) and $s - u$ crossing symmetry, we know that it must be [14, 15] that

$$F_S = isf(ln\tilde{s}), \qquad F_A = -sg(ln\tilde{s}) \tag{7}$$

where $f(z)$ and $g(z)$ are some real functions of $z = ln\tilde{s}$ where [10, 11] $|f| \quad, |g| \leq const \, ln^2 s$. We will assume that for $s > s_1 \gg 1$ the (otherwise arbitrary) functions $f(z)$ and $g(z)$ are smooth (i.e. not of an oscillatory character) functions belonging to the class of functions that asymptotically (when $|z| \to \infty$) are $|z|^{-N} \leq$

[2] If this relation is already known, we have not been able to find it in the literature.

$|f(z)|$, $|g(z)| \leq const\,|z|^2$ where N is any positive number. Then, for $s > s_1$ we can write

$$f(z) \approx f(x) - i\frac{\pi}{2}\, f'(x), \quad g(z) \approx g(x) - i\frac{\pi}{2}\, g'(x), \tag{8}$$

where $f(x)$, $g(x)$, $f'(x) = df(z)/dz|_{z=x}$, $g'(x) = dg(z)/dz|_{z=x}$ are real functions of $x = ln\, s$.

With the above definitions (and using the optical theorem), we have for the observables introduced previously

$$\frac{Re\, F_S}{Im\, F_S} = \frac{\bar{\rho}\,\bar{\sigma} + \rho\,\sigma}{\bar{\sigma} + \sigma} \approx \frac{\pi}{2}\,\frac{f'}{f}; \quad \frac{Re\, F_A}{Im\, F_A} = \frac{\bar{\rho}\,\bar{\sigma} - \rho\sigma}{\bar{\sigma} - \sigma} \approx -\frac{2}{\pi}\,\frac{g}{g'}; \tag{9}$$

$$\bar{\sigma} \approx 4\,\pi\,(f + \frac{\pi}{2}\, g'); \qquad \sigma \approx 4\,\pi\,(f - \frac{\pi}{2}\, g'); \tag{10}$$

$$\bar{\rho} \approx \frac{\frac{\pi}{2}\, f' - g}{f + \frac{\pi}{2}\, g'}; \quad \rho \approx \frac{\frac{\pi}{2}\, f' + g}{f - \frac{\pi}{2}\, g'} \tag{11}$$

where f, g, f' and g' stand for $f(x), g(x), f'(x)$ and $g'(x)$.

We can now define the following ratios of sums and differences of the quantities given above

$$RD(\rho, \sigma) \equiv \frac{(\bar{\rho} - \rho)}{(\bar{\sigma} - \sigma)} \approx -\frac{\bar{\sigma} + \sigma}{\pi\,\bar{\sigma}\,\sigma}\,\frac{g}{g'}\left[1 + \frac{\pi^2}{4}\,\frac{f'}{f}\,\frac{g'}{g}\right], \tag{12}$$

$$RS(\rho, \sigma) \equiv \frac{(\bar{\rho} + \rho)}{(\bar{\sigma} + \sigma)} \approx \frac{2\pi^2}{\bar{\sigma}\,\sigma}\left[f' + \frac{g\,g'}{f}\right]. \tag{13}$$

First of all, notice that, from (10) we clearly have $f > \frac{\pi}{2}|g'|$; thus, while it is well known that ρ will remain (asymptotically) positive, $\bar{\rho}$ will be (asymptotically) positive only if $\frac{\pi}{2}\, f' > |g|$. Next, notice that the ratios $\frac{f'}{f}$ and $\frac{g'}{g}$ decrease always at least as $const/ln\, s$ (irrespective of whether f and g grow, tend to a constant or decrease), hence, the second term in square bracket in eq.(12) can always be neglected asymptotically and the latter becomes

$$RD(\rho, \sigma) \approx -\frac{\bar{\sigma} + \sigma}{\pi\,\bar{\sigma}\,\sigma}\,\frac{g}{g'} \approx -\frac{\bar{\sigma} + \sigma}{\pi\,\bar{\sigma}\,\sigma}\,\frac{ln\, s}{K}, \tag{14}$$

where K is some constant.

Let us suppose first that g grows to infinity (i.e. we have an increasing Odderon contribution); in this case $\frac{g'}{g}$ is positive which implies K is positive. As a consequence, $RD(\rho,\sigma) < 0$. This is a direct consequence of eqs.(9). As already mentioned, this is the case found in Ref. [7] when extrapolating to higher energies and $|t|$ the fits to all existing pp and $\bar{p}p$ data . We expect that the change of sign of $RD(\rho,\sigma) < 0$ should already be observable at RHIC energies (if the measurements will not be precise enough, however, one may have to wait for LHC for an unambiguous answer). If, on the contrary, g decreases to zero as $s \to \infty$, then $\frac{g'}{g}$ is negative, K is thus negative and $RD(\rho,\sigma) > 0$. The last possible option is when g tends to a constant in which case both $\frac{g'}{g}$ positive or negative can occur. In this case, however, another correlation exists, namely $(\bar{\sigma}' - \sigma')\,(\bar{\rho} - \rho) > 0$ where we have defined $\sigma' \equiv \frac{d\sigma}{dt}|_{t=0} = \frac{1}{16\,\pi}\,\sigma^2\,\left(1+\rho^2\right).$

To see this in some detail, let us define

$$16\,\pi\,\frac{(\bar{\sigma}' - \sigma')}{(\bar{\sigma}^2 - \sigma^2)} \equiv RD(\sigma',\sigma) \equiv \left[1 + \frac{(\bar{\sigma}\,\bar{\rho})^2 - (\sigma\,\rho)^2}{\bar{\sigma}^2 - \sigma^2}\right] \approx \left(1 - \frac{f'}{f}\frac{g}{g'}\right). \tag{15}$$

When both f and g grow and $\frac{f}{g}$ also grows, we have $\frac{f'}{f}\,\frac{g}{g'} > 1$ and hence $RD(\sigma',\sigma) \to -B$ where B is some positive coefficient. As an example, one can consider the case $f(x) = A\,ln^2 s,\ g(x) = B\,ln^{\alpha} s,\ where\, 0 < \alpha < 2$ (in this case, we have also $(\bar{\sigma} - \sigma)(\bar{\rho} - \rho) < 0$). When both f and g grow and $\frac{f}{g} \to const$, $RD(\sigma',\sigma) \to 0$. As an example, consider the case $f(x) = A\,ln^{\alpha} s$ and $g(x) = B\,ln^{\alpha} s$ where $0 < \alpha \leq 2$. Finally, when f and g both grow but $\frac{f}{g}$ decreases, then we have $RD(\sigma',\sigma) \to B$ where B is some positive number[3]. As an example, consider $f(x) = A\,ln^{\alpha} s$ and

[3] This latter case is of no physical interest since it would correspond to an Odderon asymptotically dominating over the Pomeron.

$g(x) = B\, ln^{\beta} s$ with $\beta > \alpha$. Next, when f grows and $g \to const$, we have $RD(\sigma', \sigma) < 0$ if $\frac{g'}{g} > 0$ and $RD(\sigma', \sigma) > 2$ when $\frac{g'}{g} < 0$. Hence, $RD(\sigma', \sigma)\, RD(\rho, \sigma) > 0$ or $(\bar{\sigma'} - \sigma')\,(\bar{\rho} - \rho)$ is positive.

When f grows and g decreases, we have $RD(\sigma', \sigma) \to const > 1$. When $f \to const$ and g grows, we have $RD(\sigma', \sigma) > 0$ (this case was first considered by Eden [16]). When both f and g are growing, the quantity (13) $RS(\rho, \sigma) > 0$. And so on; all possibilities are easy to take into account and all correlations follow quite straightforwardly.

Let us observe that the above correlations still persist when the leading contributions cancel exactly between pp and $\bar{p}p$ and we are left purely with secondary Reggeons i.e. when $g(\tilde{s}) \approx const\,(\tilde{s})^{-\frac{1}{2}}$.

Summarizing, we have shown that a very sensitive indicator to a large C-odd contribution in the amplitude is the sign of $RD(\rho, \sigma)$ while the correlation $RD(\sigma', \sigma)$ tells us about the relative value of the C-odd contribution compared to the C-even one. Another correlation which we have not been able to prove exactly but which we strongly suspect to be correct, in the case of large asymptotic C-odd contribution is $RD(B, \sigma) \equiv \frac{\bar{B} - B}{\bar{\sigma} - \sigma} > 0$ where $B(s)$ is the slope of the diffraction peak defined as $B(s) = \frac{d(ln \frac{d\sigma}{dt})}{dt}|_{t=0}$. This relation holds true in the Regge-eikonal model with $\mathbb{P}$-O degeneracy of Ref.[13].

In conclusion, somewhat to our surprise, we have provided a host of correlations between $t = 0$ quantities (total cross sections, ratios of real to imaginary forward amplitudes and forward angular distributions) whose sign, in particular, appear quite sensitive to the existence of a growing Odderon contribution. This analysis goes quite beyond the conclusions reached in [7] where it was shown that a C-odd contribution affects rather strongly the *large*-$|t|$ data; our present results show, in

fact, that already $|t| = 0$ data may be able to decide about the existence of a relevant Odderon or not. Moreover, if the example of Ref.[7] can be taken as a guide, these correlations should already prove valid at RHIC energies [17]. The ultimate test, however, should of course come from LHC [18]. Experiments planned for these machines should check our correlations.

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